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COOL STORAGE APPLICATIONS IN THE TEXAS LOANSTAR PROGRAM: OVERVIEW AND PRELIMINARY RESULTS:

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ABSTRACT

Cool Storage Systems (CSS) are becoming a popular demand side management tool for utilities because that helps them avoid costly plant expansions and reduces summer-time peak electricity demand. This paper presents an analysis of cool storage systems in the Texas LoanSTAR program, including pre-post retrofit hourly profiles for several systems and an analysis of peak electric demand savings and energy use.

INTRODUCTION

One of the fundamental objectives of any electric utility is to maintain adequate generating capacity to meet their customers' peak demand. One of the biggest loads that many utilities in the southern United States have to face is from residential and commercial air conditioning during peak summer hours. Unfortunately, these same utilities often experience low load factors during peak summer cooling periods (ratio of energy use to peak demand) and, therefore, have to cycle their plants to meet the instantaneous loads.

The plant and the distribution network are significant investments for a utility and operating them at varying loads is inefficient. In order to combat this situation, utilities try to flatten their load profiles so that their plants can be operated at relatively constant loads and hence better efficiencies. Many electric utilities have adopted demand and energy rate schedules that vary depending on the time-of-the-day and time-of-the-month use to motivate customers to reduce their peak demand. Current trends are towards higher electric demand rates for customers in the summer during on-peak hours and lower energy use rates during off-peak summer hours.

Many electric utilities are trying to improve their load factors by adopting Demand Side Management (DSM) programs that provide incentives to their customers to reduce or shift peak loads both in the form of rate reductions and cash incentives. Cool Storage Systems (CSS) represent a technology that can provide a win-win scenario for both the utility and the customer.

In its simplest form, CSS provide cooling energy that has been produced during off-peak hours and stored for utilization during on-peak hours when the demand rate is high. In many cases, CSS may not save energy if the cooling operation is not carefully optimized and the system designed properly. However, CSS can save money for the customers because expensive peak electric rates are replaced with cheaper off-peak electric demand rates. CSS also provide valuable off-peak electricity use that helps utilities shore-up their off-peak sales.

In some cases, CSS can result in higher energy consumption because the chiller is operated at lower evaporator temperatures to produce ice or very cold chilled water, which requires the compressor to work harder to produce a greater pressure differential and raises the chiller's kW/ton. The kW/ton of ice-building chillers is, therefore, slightly higher than conventional chillers that produce chilled water in the 4°C (40°F) to 7°C (45°F) range because the chiller must operate in the -9°C (15°F) to -4°C (25°F) range. In addition, thermal storage pumps and sometimes additional chilled water pumps add to the energy consumption of the CSS. However, the higher energy consumption of CSS chillers is offset by the fact that they operate continuously during the evenings at lower ambient temperatures which helps to reduce condenser temperatures.

In many cases, CSS may save energy if the chillers were operated 24 hours/day before the CSS retrofit (often at part-load conditions). In some cases, CSS may only need to operate continuously for a few hours to charge the storage. Systems with predictive load capabilities can further reduce energy use by storing only what is needed for the forecasted weather conditions. Therefore, the energy savings or penalty due to a CSS retrofit depends on the number of hours of operation, the load on the chiller before and after the retrofit, the part-load performance characteristics of the chiller, and the thermal integrity of the insulation, etc.

In this paper, a brief description of different types of CSS is provided followed by an analysis of CSS at selected sites in the

Texas LoanSTAR program. Graphs and tables are also provided to show the pre- and post-retrofit energy consumption, demand savings, and site-specific information.

TYPES OF COOL STORAGE SYSTEMS

There are several different types of CSS depending on the storage medium and the mode of operation (Dorgan and Elleson 1993). Generally, the storage media used are ice, eutectic salt mixtures, or chilled water. The mode of operation varies from partial to full storage. The holding tanks act as the storage device during the charging mode and may also be used as a heat exchanger during the discharge mode. In some cases a separate heat exchanger may also be used to extract the stored energy from the tank to the cooling medium.

Ice Storage System

In ice storage systems, ice is generated to charge the thermal storage. Ice may be generated by using glycol or brine solutions that enter the ice tanks from the chiller and flow inside tubes at temperatures 3°C to 6°C (5°F to 10°F) below the freezing point of water. There are also the encapsulated ice storage systems (Wright 1994). In such systems deionized water is stored in plastic balls with built-in dimples. Water inside the balls is frozen as the glycol solution flows over the balls. The dimples flex to accommodate the greater ice volume. Ice can also be generated by using a direct expansion refrigeration unit where water at low heads flows directly over evaporator plates mounted above the storage tank (Knebel 1986). Ice can also be produced directly on the evaporator plates and periodically released into a holding tank below by reversing the refrigerant flow. The cooling capacity of the ice storage system depends on the heat of fusion and the rate at which ice can be melted to satisfy the cooling demand.

Eutectic Salt Storage System

Eutectic salts are another commonly used medium to store cooling energy. Eutectic salts are a mixture of inorganic salts, water, and nucleating and stabilizing agents. Like ice storage, the cooling capacity of a eutectic salt system depends on the latent heat of fusion of the salt and the amount of frozen salt. The most commonly used eutectic salt melts and freezes at 8°C (47°F). This allows conventional chillers that provide 4°C (40°F) to 6°C (42°F) discharge temperatures to be used in conditions similar to standard air conditioning. The eutectic salt has a latent heat of fusion of 19.6 kJ/kg (41 Btu/lb_m) and a density of 1,473 kg/m^3 (92 lb_m/ft^3). These eutectic salts do not expand or contract significantly during freezing or melting, and because they are heavier than water they do not float inside a tank (unlike ice ball systems) where the encapsulated eutectic salts are surrounded with water or glycol solution.

Chilled Water Storage System

Another type of storage medium is chilled water. In such systems a tank is charged with water at 4°C (40°F) to 6°C (42°F). In ideal conditions the water is stored inside the tanks in stratified layers. During the discharge mode, chilled water is supplied from the bottom of the tank and is returned to the top of the tank at low flow rates to minimize mixing of the layers. The cooling capacity of the system depends on the temperature differential across the stratified storage tank.

Full vs Partial Cool Storage Systems

As the name implies, a full cool storage system shifts the entire on-peak daytime cooling load to off-peak hours. During on-peak cooling, the storage is discharged to fully satisfy the cooling demand. Clearly, in full cool storage systems that meet the full cooling load, the storage tanks need to have enough capacity to satisfy peak cooling demand. In contrast, with partial cool storage systems only a portion of the cooling load is generated during off-peak hours and the cooling demand during on-peak hours is met with a combination of direct chiller cooling and stored cooling.

There are basically two control schemes used with partial cool storage: 1) *Chiller Priority*, where the daytime chiller is run at maximum load and any additional cooling is met from the storage, and 2) *storage priority*, where the cool storage is discharged at the maximum capacity and any additional cooling is met by the daytime chiller. With partial cool storage systems, it is important to utilize the storage at such a rate that the storage is nearly depleted at the end of the on-peak period. This requires periodical monitoring and altering of the chiller set point temperature or ice production level (Kirshenbaum 1991).

The main advantage of the partial cool storage system is that smaller chillers and storage equipment can be used and are run at near or full capacity for longer hours. Another advantage of partial storage is that in winter months it can be used as a full cool storage system, since it can meet the reduced cooling demand by itself. Partial cool storage systems also cost less and are comparable to conventional cooling systems on a first cost basis. This is because partial cool storage systems eliminate the need to purchase additional chillers large enough to generate an entire day's cooling load during off-peak hours in addition to any off-peak cooling requirements. Consequently, the associated pumps, cooling towers, and other equipment are also down-sized, resulting in lower operation costs.

Additional savings can also be obtained when CSS are coupled with specially designed cold air distribution systems, which supply conditioned air in the 4°C (40°F) to 7°C (45°F) temperature range versus the 10°C (50°F) to 14°C (57°F) range for normal systems. A cold air distribution system coupled with a partial CSS is a particularly attractive investment because of the reduced costs involved in the reduced air flow (i.e. less duct work and smaller AHUs) to the conditioned space (Rawlings 1985). In a new building this can also reduce building first costs by reducing the distance between floors and lowering electrical cable costs. Such systems have also been shown to lower summer time relative humidity which provides comfort at higher drybulb temperature settings and can even improve indoor air quality in buildings where summer time humidity control is significant (MacCracken 1986).

COOL STORAGE SITES MONITORED AS PART OF THE TEXAS LOANSTAR PROGRAM

One of the popular cooling system retrofits in the Texas LoanSTAR program has been the implementation of cool storage systems to help reduce peak whole-building electricity demand. At present, there are six sites where CSS are in place and working. These include one courthouse, four elementary/middle schools, and a hospital. The CSSs at these sites vary from ice storage using brine and glycol solutions to chilled water storage, and include partial to full storage systems. Table 1 provides general information for all six sites being monitored and includes the conditioned areas and the pre- and post- total chiller tonnage for each site.

Additional indices are also provided which are based on conditioned area, chiller tonnage, and storage capacity. These indices are helpful in making performance comparisons. Specifically, the capacity index [kWh/m^2-yr-GJ/h (Wh/ft^2-yr-ton)] and the storage capacity index [kWh/m^2-yr-GJ (Wh/ft^2-yr-ton-hr)] can indicate whether a CSS system is oversized or undersized as compared to other sites. The chiller capacity index shows the annual electricity consumption divided by the product of the conditioned area and tons of cooling capacity. The storage capacity index shows the annual electricity consumption divided by the product of the conditioned area and the cool storage capacity. Lower values for these indices reflect higher chiller cooling and storage capacity. In the next section of this paper site description and performance analysis is provided for a courthouse, one elementary school, and a hospital. Figure 1 shows the pre-retrofit whole-building electricity consumption for the courthouse during summer months from June 1, 1992 to August 31, 1992. Hourly pre-retrofit data for summer months for the other five sites were not available. Figure 2 shows the post-retrofit hourly profiles for all six sites. Figures 1 and 2 show the hourly profiles that clearly show the operation of the CSS at each of the sites in the post-retrofit period.

Midland County Courthouse (MCC)

Built in 1930, the Midland County Courthouse is a five-story 8,374 m^2 (90,100 ft^2) facility. It is constructed of reinforced concrete. The exterior walls are covered with plaster, while the interior walls consist of wood or metal studs with painted gypsum board. The facility has a built-up roof. Windows are slightly tinted and are single glazed with metal frames. The facility includes offices, courthouses and a jail on the top floor that operates 24 hours/day, 365 days/year. Other floors operate from 6:00 a.m. to 8:00 p.m. six days/week. Additional information about the building is provided in Table 1.

The electricity to the MCC is supplied by a local utility. According to the utility's rate schedule (see Table 2) the MCC is charged a demand of $6.74/kW for all demand above 10 kW. However, due to the block rate structure there are hidden

TABLE 1: DESCRIPTION OF CSS IN THE TEXAS LOANSTAR PROGRAM

LoanSTAR Site Name	Conditioned Area		# of Pre-Retrofit Chiller	Pre-Retrofit		Cool
	m2	ft2	GJ/h (tons)	Area/ total Chiller tons		Storage Type
				(m2-h/GJ)	(ft2/ton)	
Midland County Courthouse	8,374	90,100	2x1 (2x83)	4,187	543	Ice
Ward Memorial Hospital	3,439	37,000	1x1.2 (1x100)	2,866	370	Chilled Water
Oppe Elementary School	7,472	80,400	1x2.2 (1x188)	3,396	428	Ice
Weis Middle School	7,506	80,769	2x1.4 (2x120)	2,681	337	Ice
Parker Elementary School	7,597	81,742	3x1.2 (3x100)	2,110	272	Ice
Morgan Elementary School	7,137	76,798	3x1.2 (3x100)	1,983	256	Ice

LoanSTAR Site Name	Annual Elec. Use		# of Post-Retrofit Chiller	Post-Retrofit		Total Storage
	kWh/ft2-yr		GJ/h (tons)	Area/ total Chiller tons		Capacity
	Pre-	Post-		(m2-h/GJ)	(ft2/ton)	GJ (ton-hr)
Midland County Courthouse	19.9	16.6	1x2.5 (1x210)	3,349	429	13.9 (1160)
Ward Memorial Hospital	37.7	38.5	1x1.2 (1x100)	2,866	370	7.8 (653)
Oppe Elementary School	9.7	10.4	1x2.2 GJ/h, 1x0.5 (1x188, 1x45)	2,767	345	7.9 (665)
Weis Middle School	11.4	10.8	2x1.4, 1x0.7 (2x120, 1x60)	2,145	269	10.8 (902)
Parker Elementary School	9.2	10.5	3x1.2 , 1x0.7 (3x100, 1x60)	1,767	227	10.3 (862)
Morgan Elementary School	12.1	12.9	3x1.2, 1x0.8 (3x100, 1x70)	1,622	208	12.5 (1038)

LoanSTAR Site Name	On-Peak	On-Peak	Monitoring	Retrofit	Chiller Capacity Index		Storage Capacity Index	Ann. Retrofit	Annual Savings	
	Window	Months	Start-Date	Date	kWh/m2-yr-GJ/h		kWh/m2-yr-GJ	Savings ($)	$/m2	$/ft2
					(Wh/ft2-yr-ton)		(Wh/ft2-yr-ton-hr)			
					Pre-	Post-				
Midland County Courthouse	12 noon to 8 pm	Jun. to Sep.	1/7/92	Aug-92	107.6 (120)	717.7 (80)	12.5 (14)	$14,555	1.74	0.16
Ward Memorial Hospital	12 noon to 8 pm	Jun. to Sep.	1/16/92	Jun-92	3331.9 (370)	340.9 (380)	52.9 (59)	$13,195	3.84	0.36
Oppe Elementary School	1 pm to 8 pm	Year Around	12/23/92	May-93	44.8 (50)	35.9 (40)	13.5 (15)	$18,555	2.48	0.23
Weis Middle School	1 pm to 8 pm	Year Around	12/23/92	May-93	44.8 (50)	35.9 (40)	10.7 (12)	$17,092	2.28	0.21
Parker Elementary School	1 pm to 8 pm	Year Around	12/23/92	May-93	26.9 (30)	26.9 (30)	10.7 (12)	$17,291	2.28	0.21
Morgan Elementary School	1 pm to 8 pm	Year Around	12/23/92	Jun-93	35.9 (40)	35.9 (40)	10.7 (12)	$16,671	2.34	0.22

demand charges which, if taken into consideration, result in an avoided demand cost of $10.72/kW. The on-peak window is from 12:00 noon to 8:00 p.m. Monday through Friday during the calendar months of June through September. The on-peak demand during these months is set only during the demand window. There is a difference between the actual demand and the billed demand which is based on the utility's rate schedule.

TABLE 2: RATE SCHEDULE FOR THE LOCAL UTILITY FOR THE MIDLAND COUNTY COURTHOUSE & WARD MEMORIAL HOSPITAL

Demand Charge:
$6.74/kW of demand in excess of 10 kW
Demand Determination:
A. Demand is the smaller of:
1) current month kW.
2) on-peak kW plus 25% of the current month kW in excess of the on-peak kW.
B. But Demand is not less than the highest of:
1) 80% of on-peak kW;
Current month kW is the highest 15-minute kW recorded at the point of delivery during the current month.
On-peak kW is the highest 15-minute kW recorded during the billing months of June through September in the 12-month period ending with the current month.
On-peak hours are weekday hours between 12 noon and 8 p.m., excluding July 4 and Labor day during the calendar months of June through September.
Energy Charges:
$0.0572/kWh for first 2500 kWh
$0.0300/kWh for next 3500 kWh
$0.0066/kWh for all additional kWh

The local utility has a ratchet clause according to which the customer is billed for 80% of the on-peak demand if the off-peak month's demand drops below 80% of the on-peak demand. The utility also charges 25% of any off-peak month's demand which is in excess of the on-peak demand.

The LoanSTAR monitoring at the MCC began in January 1992. The ice storage system was installed in August 1992. As part of the retrofit, a 2.5 GJ/h chiller (210-ton) was installed in place of the two existing 1 GJ/h chillers (83-ton each, 166-tons total). The MCC has a full-load ice storage system. There are eight tanks with individual capacities of 1.7 GJ (145 ton-hr). The total storage capacity of the system is approximately 13.9 GJ (1,160 ton-hr). The CSS uses a brine solution that is fed to the ice tanks from the chiller at -3°C (26°F). Ice is generated and stored in the tanks. As the amount of ice in the tanks increases the discharge temperature gradually drops. When the system reaches full storage capacity, the return temperature of the brine drops to -2°C (28°F), at which point the chiller is shut off. During the discharge mode, the same brine solution flows through the tanks to the cooling coils in the AHUs. The discharge temperature of the brine remains around 1°C (33°F). Air is supplied at 13°C (55°F) to the conditioned space. During the local utility's on-peak months (June through September) the charging starts at 8:00 p.m. and continues until the early morning hours, when the tanks are fully charged at which point the chiller shuts off. During the occupied period before the onset of the demand window, the building is conditioned by direct chiller cooling. The chillers are then taken off-line from noon to 8:00 p.m., which is the utility's on-peak window. The building is conditioned during the on-peak hours by using only the stored cooling.

Figures 1 and 2e show the pre- and post-retrofit whole-building electricity consumption during the summer months from June 1 to August 31 in 1992 (Figure 1) and 1993 (Figure 2e) respectively. Figure 1 shows that before the retrofit the chillers were run 24 hours/day and the building operated straight through the local utility's on-peak window. It should be noted that during the pre-retrofit period, the MCC had two chillers each rated at 1 GJ/h (83 tons each, 166 tons total).

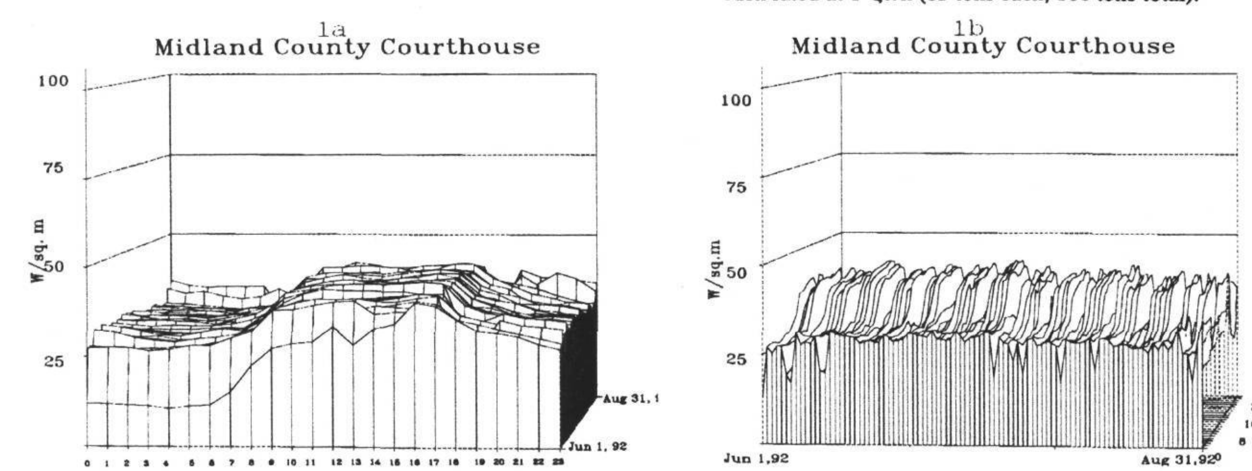

FIGURE 1A, 1B: PRE-RETROFIT WHOLE-BUILDING ELECTRICITY CONSUMPTION DURING THE SUMMER MONTHS FOR THE MIDLAND COUNTY COURTHOUSE. FIGURE 1A DISPLAYS THE DATA AS A SERIES OF 24-HOUR DAILY PROFILES. FIGURE 1B SHOWS THE PROFILES IN TIME SERIES FROM LEFT TO RIGHT FOR THE PERIOD JUNE 1, 1992 THROUGH AUGUST 31, 1992.

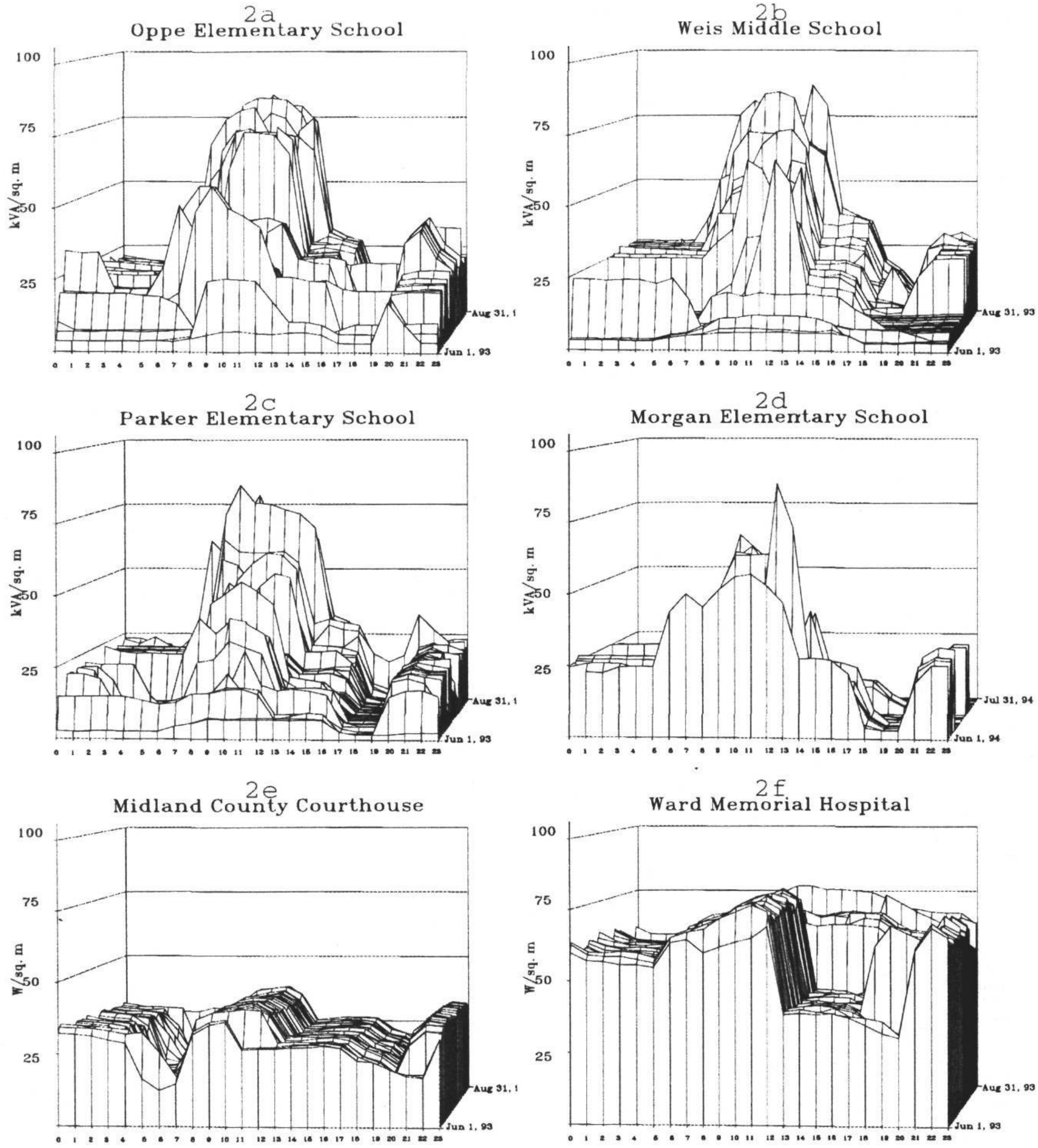

FIGURE 2A-2F: POST-RETROFIT WHOLE-BUILDING ELECTRICITY CONSUMPTION DURING THE SUMMER MONTHS FOR LOANSTAR SITES WITH COOL STORAGE SYSTEM. FIGURES 2A-2D SHOW THE WHOLE-BUILDING POST-RETROFIT USE FOR THE OPPE, WEIS, PARKER, AND MORGAN SCHOOLS IN GALVESTON, TEXAS. FIGURE 2E SHOWS THE MIDLAND COUNTY COURTHOUSE IN MIDLAND, TEXAS. FIGURE 2F SHOWS THE WARD MEMORIAL HOSPITAL IN MONAHANS, TEXAS.

After the retrofit (Figure 2e), the change in operating hours and the effectiveness of the CSS retrofit can clearly be seen. The chiller is shut down at noon (the shut down at noon shows up at the next hour, i.e. 13 hours) and is started again at 8:00 p.m. (which shows up at 21 hours) to charge the CSS. It is interesting to note that there are dips during the early morning which are due to the varying amount of time required by the chiller to charge the CSS, depending on the ambient conditions and how much ice was carried over from the previous day. These dips roughly indicate a small potential for additional savings from an optimal CSS start time. In such a system the start of the chillers would be delayed to match the required cooling load. Savings would occur from reduced storage losses. Varying amounts of ice could also be stored for reduced cooling demands if a predictive controller could be facilitated.

Figure 3 shows the monthly averaged utility billing demand for three years before the retrofit and the monitored demand for one year after the retrofit. It can clearly be seen that during the pre-retrofit period, the billed demand is higher in the summer months. This also affects the billed demand during winter months because of the ratchet clause. After the retrofit, there is an appreciable drop in the billed demand and the demand remains fairly constant throughout the year, mainly because the chiller load is shifted to off-peak hours.

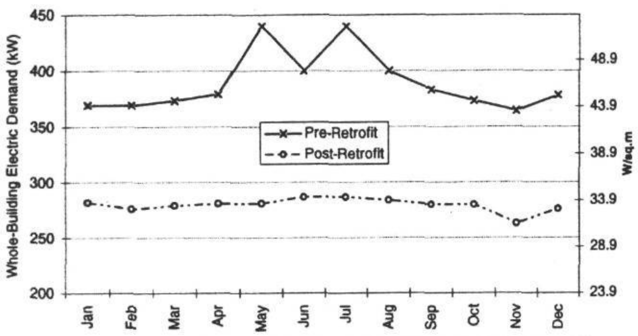

FIGURE 3: MONTHLY AVERAGED UTILITY BILLING DEMAND FOR THREE YEARS BEFORE THE RETROFIT AND MONITORED DEMAND AFTER THE RETROFIT FOR MIDLAND COUNTY COURTHOUSE.

Figure 4 shows the pre- and post-retrofit whole-building electricity consumption plotted against the average billing period ambient temperature for the courthouse. Clearly the electricity consumption of the courthouse has decreased after the retrofit. The drop in electricity consumption, however, is most likely due to additional retrofits that took place at the same time as the CSS, such as installation of an energy management controls system, occupancy sensors, modification of chiller piping and controls, and electronic ballasts for the fluorescent lighting. Unfortunately, due to the limitation of sub-metered data it is not possible to assess and isolate the change in the electricity consumption due to the CSS retrofit alone. Figure 4 also shows that the electricity consumption increases at lower ambient temperatures which is due to electric heating in the building.

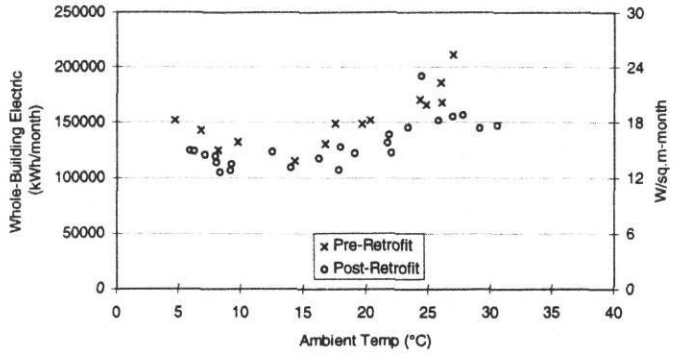

FIGURE 4: MONTHLY WHOLE-BUILDING ELECTRICITY CONSUMPTION BEFORE AND AFTER THE RETROFIT VERSUS AVERAGE MONTHLY AMBIENT TEMPERATURE FOR MIDLAND COUNTY COURTHOUSE.

The chiller capacity index of 71.7 kWh/m^2-yr-GJ/h (80 Wh/ft^2-yr-ton) and storage capacity index of 12.5 kWh/m^2-yr-GJ (14 Wh/ft^2-yr-ton-hr) indicate that at the MCC the storage is sized about the same as the four schools in Galveston, all of which are operating successfully.

The annual cost saving due to the demand reduction at the MCC from June 1993 to May 1994 has been $14,555 ($1.74/m^2, $0.16/ft^2). The demand savings are based on the difference between the actual post-retrofit monthly demand and a pre-retrofit model that has three years of historical utility demand data.

Oppe Elementary School (OES)

Oppe Elementary School is one of the four schools in the Galveston Independent School District participating in the Texas LoanSTAR program. OES was constructed in 1987 and is a single-story building with a gross area of 7,472 m^2 (80,400 ft^2). It has pre-fabricated panel-type construction with face-brick walls and a built-up roof. The school is occupied from 7:00 a.m. to 4:00 p.m. during weekdays for nine months of the year and is unoccupied on the weekends. The school also remains occupied for about an hour and a half for a few days after 4:00 p.m. for staff meetings. The school is closed down for summer around the last week of May or the first week of June. However, the school remains occupied by the Principal and supporting staff for a few weeks into the summer break. The school re-opens in August for the fall session. Additional information about this school and the other three Galveston schools is provided in Table 1.

Electricity to the school is supplied by a local utility whose electric rate schedule is provided in Table 3. The on-peak demand window for the utility is from 1:00 p.m. to 8:00 p.m. Monday through Friday throughout the year. The demand charge is $3.40 /kVA. An energy charge is based on a block rate structure with separate charges for summer and winter months. Because of the block rate structure, any savings in kVA demand results in a shift in energy charge from a higher rate to a lower rate. The net effect is that the avoided demand cost increases from $3.40/kVA to $5.88/kVA, thus yielding a much higher savings.

TABLE 3: RATE SCHEDULE FOR THE OPPE ELEMENTARY SCHOOL

Demand Charge: \$3.40/kVA x month for each billing kVA over 10 kVA (from 1:00 p.m. to 8:00 p.m.)
Energy Charge: May through October 1) Billing kVA x 125 kWH/kVA x \$0.0569370 2) Billing kVA x 170 kWH/kVA x \$0.033279 3) \$0.007313 for all additional kWH November through April 1) Billing kVA x 125 kWH/kVA x \$0.0532810 2) Billing kVA x 170 kWH/kVA x \$0.033279 3) \$0.007313 for all additional kWH

Before the retrofit, the OES had one 2.3 GJ/h-chiller (188-ton) which operated continuously during peak hours in the summer. This resulted in the chiller being operational during the utility's 1:00 p.m. to 4:00 p.m. on-peak window. Occasionally, the chiller remained operational during after-hours staff meetings, which is estimated to require 1.3 GJ (110 ton-hr) of cooling. The CSS was, therefore, designed to shift a total load of about 7.9 GJ (2.2 GJ/h x 3 hrs + 1.3 GJ) (665 ton-hr) to off-peak hours. As part of the LoanSTAR retrofit, a thermal storage chiller was installed that is sized to build up the required storage capacity in 15 hours, thereby providing a safety factor of two hours. A new EMCS system was also installed so that control set points for all the schools can be monitored and changed via modem from a single PC located in the district energy manager's maintenance office.

As part of the LoanSTAR program, the whole-building electricity consumption (kWh/15-min and kVAr/15-min) and the kWh/15-min of the one 2.3 GJ/h-chiller (188-ton) is being monitored. After the retrofit, a new CSS chiller was installed and will be monitored during the 1994/1995 school year provided monitoring funds are available. The electricity consumption of the new chiller is, however, reflected in the whole-building signal. This is shown in Figure 2a where the hourly post-retrofit whole-building electricity consumption for the OES is plotted as a 3-D time-series plot. Figure 2a shows that the thermal storage chiller is usually turned on at 8:00 p.m., and operates continually until the storage is fully charged or until 1:00 p.m., whichever comes first. Frequently, the 2.3 GJ/h (188-ton) chiller is also turned on in the early morning hours to provide additional cooling but is invariably turned off at the onset of the on-peak hours, resulting in a very big drop in the whole-building electricity consumption. The high electric demand due to the operation of both the chillers does not cost the school because this occurs during off-peak hours only.

Figure 5 shows the pre- and post-retrofit kVA demand for OES. The pre-retrofit demand is based on monthly averaged utility billing data for three years and the post-retrofit demand is based on LoanSTAR monitored 15-minute kVA data from May, 1993 to April, 1994. It can be seen that there is an appreciable drop in kVA demand throughout the year. The reason for this was that during the pre-retrofit mode, the chillers were run from morning until evening hitting their peak during the on-peak demand window.

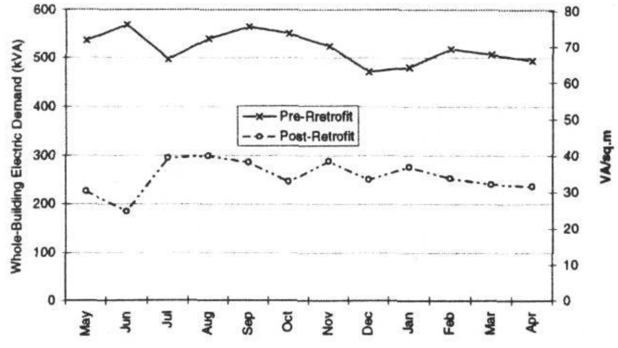

FIGURE 5: MONTHLY AVERAGED UTILITY BILLING DEMAND FOR THREE YEARS BEFORE THE RETROFIT AND THE MONITORED DEMAND AFTER THE RETROFIT FOR OPPE ELEMENTARY SCHOOL.

Figure 6 shows the pre- and post-retrofit whole-building electricity consumption plotted against ambient temperature for the OES. It can be seen that there are basically two sets of data clusters, one during school months (i.e. > 50,000 kWh/month) and the other during summer months of June and July when the school is mostly closed. During the school months in the post-retrofit the whole-building electricity consumption has more or less remained unchanged as shown by the evenly scattered data points in the pre- and post-retrofit periods.

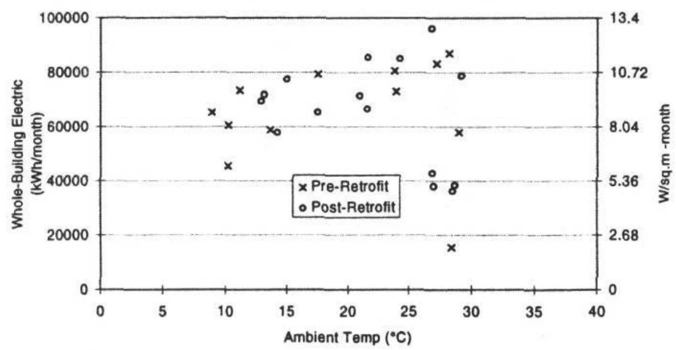

FIGURE 6: MONTHLY WHOLE-BUILDING ELECTRICITY CONSUMPTION BEFORE AND AFTER THE RETROFIT VERSUS AVERAGE MONTHLY AMBIENT TEMPERATURE FOR OPPE ELEMENTARY SCHOOL.

The chiller capacity index of 35.9 kWh/m^2-yr-GJ/h (40 Wh/ft^2-yr-ton) may be indicating that the chillers are slightly oversized compared to the MCC. However, the storage capacity index of 13.5 kWh/m^2-yr-GJ (15 Wh/ft^2-yr-ton-hr) seems to indicate similar sized as the MCC.

The annual cost saving due to the demand reduction at the OES from June 1993 to May 1994 has been \$18,555 (\$2.48/m^2, \$0.23/ft^2). The demand savings are based on the difference between the actual post-retrofit monthly demand and monthly averaged data from three years of historical utility demand data.

Ward Memorial Hospital (WMH)

Ward Memorial Hospital was constructed in 1980 and has 3,439 m^2 (37,000 ft^2) of conditioned floor area. The walls are pre-cast and the roof is built-up. The windows are bronzed 0.6 cm (1/4") photo glass with mirror finish. The hospital is occupied 24 hours a day, 365 days/year, although there is a 50% reduction in load from 7:00 p.m. to 6:00 a.m. The hospital is supplied with electricity from a local utility whose electric rate schedule is provided in Table 2.

The existing chiller in the hospital has a capacity of 1.2 GJ/h (100 tons) at 4°C (7°F) temperature differential for a flow rate of 23 liters/sec (360 gpm). There are four reciprocating compressors, each with a capacity of 0.3 GJ/h (25 tons). The cool storage in the hospital was installed in June, 1992 and uses stratified chilled water storage. The thermal storage tank is designed to hold 305,000 liters (80,600 gallons) of water at 4°C (40°F). The system was designed to provide a total storage capacity of 7.8 GJ (653.2 ton-hr) by supplying chilled water at 4°C (40°F) to the AHUs' cooling coils which operate at 11°C (52°F).

The storage system was designed so that the chiller is turned on at 8:00 p.m. each day to charge the storage and at the same time cool the building directly. During charging, 8 liters/sec (125 gpm) of chilled water is supplied to the bottom of the tank and the remainder to the AHUs' cooling coils. The return water to the chiller is a combination of return water from the building and 8 liters/sec of return water from the top of the storage tank. The four reciprocating compressors are controlled by the return water temperature to the chiller and are sequenced to shut off in stages as the return water temperature drops down from 7°C (44°F) to 6°C (42°F). During the discharge mode, chilled water at 4°C (40°F) is pumped from the bottom of the tank to the cooling coils and is returned at 11°C (52°F) to the top of the tank at very low flow rates in order to minimize turbulence, which can cause mixing of the stored chilled water with the return water. During discharge the thermocline (interface of the 4°C water and the 11°C water) drops gradually as the tank fills up with water at 11°C (52°F). During recharging, the storage water is recycled through the chiller until it attains the desired storage temperature of 4°C (40°F).

Unfortunately, CSS at the Ward Memorial Hospital has not lived up to expectations. It is speculated that the existing chiller does not have enough capacity because it is required to cool the building directly at the same time it is required to charge the thermal storage. The building also has significant internal heat generation 24 hours a day and therefore requires substantial cooling, even during the charging period. The chiller capacity index of 340.1 kWh/m^2-yr-GJ/h (380 Wh/ft^2-yr-ton) and storage capacity index of 52.9 kWh/m^2-yr-GJ (59 Wh/ft^2-yr-ton-hr) are substantially higher than any of the other LoanSTAR sites.

The chiller is designed to shut off in stages as the return water temperature drops. According to the Hospital personnel, during warm weather, due to the mixing of return water from the building and from the top of the tank, the mixed return water temperature does not drop down low enough and the chiller remains energized until it is forced to shut off at 12 noon at which point the storage is not fully charged (Clark 1994). During the following day the stored capacity is not enough to last through the entire on-peak period and the chiller has to be energized to satisfy the load during peak periods. It is speculated that another problem might be that the total stored capacity of the tank cannot be fully utilized. As the thermocline drops (i.e. warm water enters the tank), there is increased turbulence which promotes the mixing of the 4°C (40°F) water and the 11°C (52°F) water near the bottom of the tank, thereby increasing the supply temperature.

Figure 2f shows the post-retrofit whole-building electricity consumption for the hospital as a 3-D time-series plot. Figure 2f shows that on most days the chiller is shut off at noon and is turned on again at 8:00 p.m. However, on the hottest days the chiller is energized during on-peak hours because the storage has been depleted before the onset of the off-peak hours. An investigation of the data revealed that during all three seasons in 1992, 1993, and 1994, the chiller had to be energized for several days during on-peak hours resulting in no actual demand savings. However, the management at WMH made an arrangement with the local utility whereby the utility ignored the on-peak demand during a few days when the chiller had to be energized. This is a temporary arrangement until the system can be modified.

Figure 7 shows the potential pre- and post-retrofit demand for the hospital (i.e., it ignores the actual post-retrofit demand during peak months on problem days). Figure 7 shows that the drop in demand from June to September is significant and results is savings throughout the year because WMH is only charged for 25% of the demand in excess of the peak-demand set between June and September. The successful completion of the retrofit will mean that the WMH could enjoy an average annual cost savings of $13,195 ($3.84/m^2, $0.36/$ft^2$).

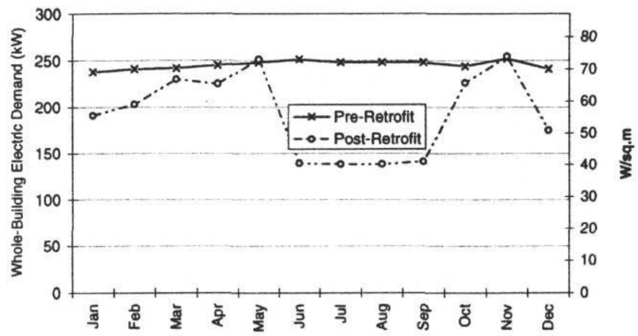

FIGURE 7: MONTHLY AVERAGED DEMAND BEFORE THE RETROFIT AND THE MONITORED DEMAND AFTER THE RETROFIT FOR WARD MEMORIAL HOSPITAL (IGNORING DEMAND ON PROBLEM DAYS).

An analysis of the electricity use at the WMH reveals an unexpected benefit of the system. Before the retrofit, the chiller at WMH was operated for 24 hours/day which meant that the chiller was often run at part-load conditions during the evenings. After the retrofit, the chiller is operated continuously (charging cool storage and direct cooling) for a fewer number of hours and is turned off on most days during the on-peak hours. As a result, the increased electricity consumption due to the associated pumps and equipment is nearly offset by fewer hours of operation of the chiller and the improved operation of the chiller during cool evenings. This is indicated in Figure 8 which shows nearly equal pre- and post-retrofit electricity consumption plotted against the average monthly ambient temperature.

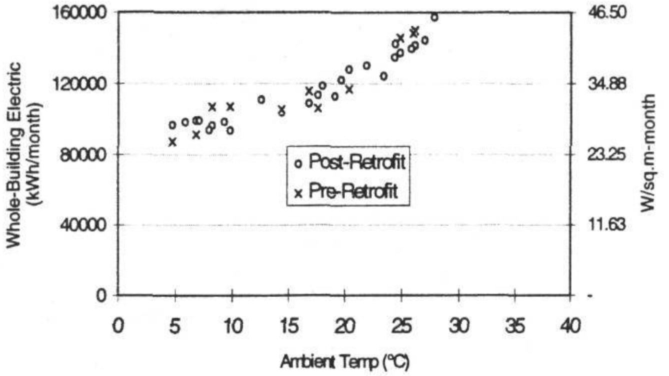

FIGURE 8: MONTHLY WHOLE-BUILDING ELECTRICITY CONSUMPTION BEFORE AND AFTER THE RETROFIT VERSUS AVERAGE MONTHLY AMBIENT TEMPERATURE FOR WARD MEMORIAL HOSPITAL.

SUMMARY

This paper has presented a brief overview of the CSS and has provided a look at hourly before-after monitoring of the CSS in the Texas LoanSTAR program. Peak demand savings in the LoanSTAR CSS are performing near to the expected levels. A preliminary look at the thermal energy penalties for using the CSS shows that these penalties have been minimized due to careful construction and efficient system operation.

A closer look at Table 1 reveals that the whole-building electricity consumption (kWh/ft^2-yr) has remained nearly unchanged at all the sites due to the CSS retrofit. An exception to the case is the MCC, where the whole-building electricity consumption has decreased after the retrofit but this is most likely attributable to other retrofits that were also implemented along with the CSS.

The pre- and post- indices in Table 1 show that the conditioned area per cooling capacity of the chiller (m^2-h/GJ & ft^2/ton) indicate that for all the sites except the WMH, the pre index is greater than the post index. This is because in these sites either a larger capacity chiller was installed (MCC) or an additional chiller was installed (schools) that is only dedicated to making ice or charging the thermal storage. These indices, however, vary across sites and do not single out any problematic sites.

The problem at the WMH is clearly shown by the storage and chiller capacity indices. The chiller capacity index at WMH is about 5 times higher than at the MCC and about 10 times higher than at the Galveston schools. Similarly, the storage capacity index for the WMH is about 4 to 5 times higher than at any other site where the cool storage systems are performing adequately. Simplified indices such as these may provide useful cross-check for utilities and building owners to prevent the improper design and installation of cool storage systems.

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